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Impact of palm, mustard, waste cooking oil and *Calophyllum inophyllum* biofuels on performance and emission of CI engine

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ABSTRACT

Present energy situation of the world is unsustainable due to unequal geographical distribution of natural wealth as well as environmental, geopolitical and economical concerns. Ever increasing drift of energy consumption due to growth of population, transportation and luxurious lifestyle has motivated researchers to carry out research on biofuels as a sustainable alternative fuel for diesel engine. Renewability, cost effectiveness and reduction of pollutants in exhaust gas emission are promoting biofuels as a suitable substitute of diesel fuel in near future. This paper reviews the suitability of feedstock and comparative performance and emission of palm, mustard, waste cooking oil (WCO) and *Calophyllum inophyllum* biofuels with respect to diesel fuel from various recent publications. Probable analysis of performance and emission of biofuel is also included in further discussion. Palm oil has versatile qualities in terms of productivity, oil yield and land utilization. But tremendous demand of edible oil is motivating the use of non-edible vegetable oils as biofuel feedstock. Mustard oil is a promising new biofuel especially regarding NO_x reduction. WCO is one of the most economic sources of biofuel which efficiently helps in liquid waste management and prevents recycling of used oil, injurious to human health. *C. inophyllum* is completely non-edible and trans-esterified oil shows similar engine performance and emission characteristics like other biofuels. Limited data were published regarding mustard and *C. inophyllum* as their use as biofuel is still in primary state compared to palm or WCO. Therefore, in depth research needs to be carried out on these two oils to use them effectively as alternative fuels.

Contents

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1. Introduction

Modern civilization is very much dependent on non-renewable fossil resources like coal, petroleum and natural gas [1]. In recent years, ever increasing trend of energy consumption due to industrialization and development has caused serious threat to the energy security and environment. Global fossil fuel consumption grew 0.6 million barrels per day and cost $ 111.26 per barrel in 2011 which means a 40% increase than 2010 level [2]. Current reserve of liquid fuel has the capacity to meet only half of the usual energy demand until 2023 [3]. Besides, this tremendous drift of fossil fuel use, hazardously effecting world′s environment, which includes global warming, deforestation, eutrophication, ozone depletion, photochemical smog and acidification [4].

Major portion of the petroleum and natural gas reserve is distributed within a small region of the world. Middle East countries are the dominant petroleum suppliers and possess 63% of global petroleum reserve [5]. On contrary, Renewable energy sources are more evenly distributed than fossil fuel and hence, coming up as a secured energy source in near future. Greater energy security, reducing environment pollution, saving foreign exchange and other socio-economic issues stimulating the rapid growth of biofuel industries over the next decade [6]. Staniford demonstrated a projection back in 2008 on global marketed primary energy production from 1970 to 2050 which strongly supports the increasing trend of renewable energy consumption [7]. Projection is shown in Fig. 1. U.S Energy Information Administration (EIA) also showed a similar projection which was projected until 2035 [8]. In a reference case, showed by EIA, renewable energy possessed 10% share of the total energy used in 2008 and it will be increased to 14% in 2035. They mentioned renewable energy as world′s fastest growing form of energy. Biodiesel is progressively gaining acceptance as an alternative and renewable energy source and market demand will rise intensely in near future [9–11]. According to International Energy Agency (IEA), around 27% of total transport fuel will be replaced completely by biofuels within 2050 [12].

Vegetable oils are quite favourable alternative fuels for diesel engines. Biodiesel fuels are mono alkyl esters and generally derived from fatty ester of vegetable oil or animal fat [13,14]. Suitable sources of biodiesel vary from country to country depending upon available vegetation and environmental conditions. Crude vegetable oils are not suitable as engine fuel in terms of lower heating value, high viscosity, low volatility, freezing point etc. But many chemical treatments are available to improve physicochemical properties of crude vegetable oils. Transesterification is the most popular chemical treatment to reduce viscosity and achieve diesel like properties [15]. Standard specifications and test methods of ASTM and EN are given at Table 2. Transesterified vegetable oils are widely being used in diesel engines at present [16]. Biodiesels and their blends have similar properties as diesel fuel and are favoured due to lower exhaust emission. Moreover, all

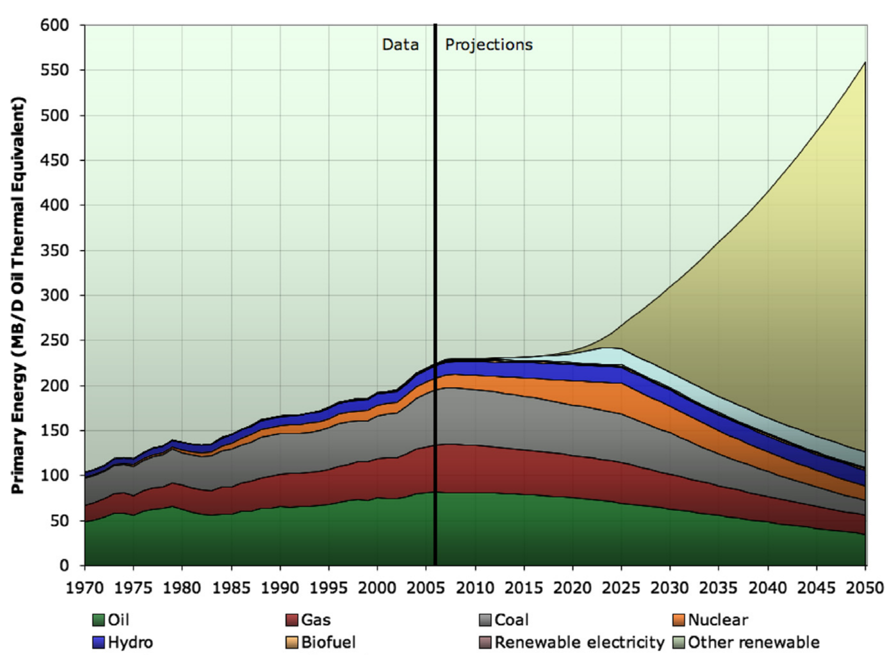

Fig. 1. Projection of global marketed primary energy production 1970–2050 [7].

Table 1
Comparative physical and thermal properties of fossil diesel, palm, mustard, WCO and *Calophyllum inophyllum* biodiesel.

Fuel property Unit	Density at 288 K kg/m^3	Calorific value MJ/kg	Flash point K	Pour point K	Kinematic viscosity at 300 K mm^2/s	Carbon residue wt%	Cetane number –	Iodine value mg I/g	Reference –
Diesel	816–840	42–45.9	323–371	238–258	2.5–5.7	0.35–0.4	45–55	49–65	[36–40]
Palm oil biodiesel	864–871.6	37.4–38.2	408	287–289	4.05–5.1	–	58–65.5	44–65	[4,37,41–44]
Mustard oil biodiesel	880–882	32–33	431	261	24–26	–	50	50–54	[45–47]
Waste cooking oil biodiesel	820–897	38–43	469	260–275	4.4–5.5	0.33	46–60	108–128	[39,41,48–50]
Calophyllum inophyllum	869	41.397	413	277–279	3.90–4.0		57	–	[26,51,52]

Table 2
Standard property specifications for biodiesel and test methods (B100) [4,36,53–55].

Property	Units	ASTM-D6751	ASTM test method	EN-14214	EN test method
Density at 288 K	g/cm^3	–	–	0.86–0.90	EN ISO 3675 or 12185
Viscosity at 313 K	mm^2/s	1.9–6.0	D445	3.50–5.00	EN ISO 3104
Flash point	°C	130min	D93	120 min	EN ISO 3679
Cetane number		47min	D613	51 min	EN ISO 5165
Carbon residuea	% mass	0.05 max	D4530	–	–
Iodine value	–	–	–	120 max	EN14111
Oxidation stability, at 383 K	h	–	–	6 min	EN 14112
Acid number	mg KOH/g	0.80 max	D664	0.50 max	EN 14104
Sulphur content	mg/kg	15.0 max	D 5453	10.0 max	ENISO 20846; EN ISO 20884
Water content	mg/kg	500 max	D2709	500 max	EN ISO 12937
Phosphorus content	mg/kg	10.0 max	D 4951	10.0 max	EN 14107
Free glycerine	% mass	0.02 max	D6584	0.02 max	EN 14105, EN 14106
Total glycerine	% mass	0.24 max	D6584	0.25 max	EN 14105
Sulfated ash content	% mass	0.02 max	D874	0.02 max	ISO 3987
Methanol content	% mass	–	–	0.20 max	EN 141110
Monoglycerides	% mass	–	–	0.80 max	EN 14105
Diglycerides	% mass	–	–	0.20 max	EN 14105
Triglycerides	% mass	–	–	0.20 max	EN 14105
Ester content	% mass	–	–	96.5 min	EN 14103
Linolenic acid methyl ester	% mass	–	–	12.0 max	EN 14103
Copper corrosion (3 h, at 323 K)	Degree of corrosion	No. 3	D130	No. 1	EN ISO 2160
Distillation 90% recovered	°C	360 max	D 1160	–	–

carbons released by the combustion of biofuel are fixed by the plant through the process of photosynthesis. This is the concept of "carbon neutral fuel", emphasized by Kyoto Protocol, which establishes the contribution of using biofuel in the prevention of global warming [17]. On the contrary, high viscosity and low volatility results in poor combustion which are the main drawbacks of vegetable oil.

This review is focused on the possibilities and comparative evaluation of using palm, mustard, WCO, and *Calophyllum inophyllum* biofuels in diesel engine. In most of the papers reviewed here, research was carried out on vegetable oils and their blends. For this reason, vegetable oil and biodiesel both are discussed and named under the title biofuel. Palm is the most productive plant among all biofuel feed stock. Mustard oil is also a potential feedstock of biofuel. In most of the literatures reviewed, it was found that low-quality seeds which are unsuitable for food use, are adopted for fuel production [18]. Canola or rapeseed has gained widespread acceptance as biodiesel feedstock which is from the same plant family of mustard. But advantage of mustard oil is, it contains high amount of erucic acid which makes it less edible and generally is used as condiment. Therefore, mustard oil is suitable for industrial use and unlike canola using mustard as biodiesel feedstock would not intensely interfere with the food supply [19]. Another major advantage of mustard oil is that it reduces NO_x emission than diesel or any other biofuels. Therefore, mustard is seemed to be a more feasible feedstock for biodiesel production [20].

More than 95% of world's biofuel production is produced from edible oils [21–23]. However, producing biofuel from edible oil

Table 3
Typical fatty acid composition of palm, mustard, WCO and *Calophyllum inophyllum*. (wt%) [4,18,39,41,45,56–58].

Fatty acid (*xx:y*)	Palm oil	Mustard oil	Waste cooking oil	*Calophyllum inophyllum*
Lauric acid (C12:0)	0.1	–	–	–
Myristic acid (C14:0)	1.0	0.063	–	–
Palmitic acid (C16:0)	42.8	2.377	8.5	12.01
Palmitoleic acid (C16:1)	–	0.180	–	–
Heptadecanoic acid (C17:0)	–	0.018	–	–
Heptadecanoic acid (C17:1)	–	0.043	–	–
Stearic acid (C18:0)	4.5	1.253	3.1	12.95
Oleic acid (C18:1)	40.5	25.156	21.2	34.09
Linoleic acid (C18:2)	10.1	14.459	55.2	38.26
α-linoleic acid(C18:3)	0.2	15.451	5.9	0.3
Arachidic acid (C20:0)	–	1.338	–	–
Eicosenoic acid (C20:1)	–	0.423	–	–
Heneicosanoic acid (C21:0)	–	0.838	–	–
Erucic acid (C22:1)	–	36.709	–	–
Docosadienoic acid (C22:2)	–	0.286	–	–
Nervonic acid (C24:1)	–	1.405	–	–
Others	0.8	–	4.2	2.4
Saturates (%)	44.7	5.9		
Unsaturates (%)	55.3	94.1		

source has received criticism from several non-governmental organisations worldwide [22]. Therefore, using non-edible vegetable oils as biofuel which are not suitable for human food can replace the current dependence on the edible oil source. Though WCO is being recycled by some companies recently, but recycled WCO causes various health hazards to human health. Oxidized cooking oil contains many toxic substances which may lead to cancer in human body, if used again [24]. In some poor countries, WCO is recycled to use again. Thus, increasing the use of WCO as biofuel could prevent its recycling for further use. Moreover, WCO is 2 to 3 times cheaper than other vegetable oils. *C. inophyllum* can be transesterified and is a very promising non edible source of biofuel. Its production is still in nascent state compared to palm biodiesel industry.

Engine performance parameters like Brake Specific Fuel Consumption (BSFC), Brake Thermal Efficiency (BTE) and Brake power are discussed for each biofuel separately. Research findings of different emission characteristics like Exhaust Gas Temperature (EGT), Smoke opacity, Carbon monoxide (CO), Hydrocarbon (HC), NO_x, Carbon di Oxide (CO_2) and Particulate Matter (PM) are also presented for each biofuel following their respective performance discussions. Finally, all findings of performance and emissions are summarised in Table 5 and Table 6 and analysis of the results are discussed in the later part based on fuel properties and engine operating conditions.

Table 4
Dialectal names of *Calophyllum inophyllum* in different regions of the world [115–117].

Country	Common names
Bangladesh	Punnang
Cook Island	Tamanu
Cambodia	Kchyong, Khtung.
English	Beach mahogany, Alexandrian laurel, Beauty leaf, Ball nut.
Fiji	Dilo
Guam	Da′ok, Da′og
Hawaii	Kamanu, Kamani
India	Poon, Polanga, Undi, Sultan champa.
Indonesia	Bintangur, Nyamplung
Kiribati	Te itai
Malaysia	Bintangor, Penang laut
Marquesas	Tamanu
Myanmar	Ponnyet
Northern Marianas	Da′ok, Da′og
Nauru	Tomano
Palau	Btaches
Papua New Guinea	Beach calophyllum
Philippines	Bitaog, Butalau, Palo maria
Solomon Islands	Dalo
Society Islands	Tamanu
Tahiti	Tamanu
Thailand	Naowakan, Krathing, Saraphee

2. Palm oil

Palms are most popular and most extensively cultivated amongst the plant families. Around 202 genera and approximately 2600 species of palms are currently known and available mostly at tropical, subtropical and climates where weather is warm. Among them, oil palm is originated from the species *Elaeis guineensis* belongs to genus *Elaeis* and family *Palmae* [25]. Basically oil palm tree is originated from West Africa where it was growing wild and human started using palm oil 5000 years ago [26,27]. Discovering its economic benefits cultivation of palm oil gained popularities in all tropical areas of the world.

Worlds total palm oil production is 45 million tonnes per year and maximum production is in South East Asia [28,29]. Percentage of palm oil production at different countries is shown in Fig. 2. About 87% of world palm oil production is contributed by Malaysia, Indonesia and Thailand. From 1990 to 2009 palm crop plantation area increased from 2.03 to 4.49 million hectares in Malaysia which means an increase of 121.2%.

Elaeis Guineensis Jacq is the most highly productive species and can be cultivated in all tropical areas where weather is humid and hot like Malaysia and Indonesia. This particular variety can annually produce 10–35 t/ha of palm fruits [26]. Comparison of oil production per hectare of palm with other biofuel feedstock is shown in Fig. 3. A single stemmed, matured palm tree can grow up

Table 5
Research findings of different performance parameters for palm, mustard, WCO and *Calophyllum inophyllum* biofuel.

Performance parameter	Palm oil	Mustard oil	Waste cooking oil	*Calophyllum inophyllum*
BSFC increase	Blended: Lin et al. [64], Preheated: de Almeida et al. [71], Blended: Yusaf et al. [60], Blended: Ndayishimiye and Tazerout [61], Degummed deacidified crude: Leevijit and Prateepchaikul [59], Methyl and ethyl ester of palm oil: Ndayishimiye and Tazerout [61] Biodiesel: Aziz et al. [66]	Methyl ester: Bannikov [81], Rattan and Kumar [78], Blended: Hasib et al. [79], Blended: Azad et al. [46]	Blended: Lin et al. [93], Waste frying palm oil and its blends: Ozesezen and Canakci [48], Methyl Ester of waste olive oil: Dorado et al. [103], Methyl ester of waste frying oil: Utlu and Koçak [94]	Methyl Ester: Venkanna and Reddy [122], Mixed: Bora et al. [125]
BSFC decrease		Blended: Anubumani and Singh [47]		
BTE increase	Preheated: de Almeida et al. [71], Blended: Ndayishimiye and Tazerout [61], Biodiesel: Satyanarayana and Muraleedharan [65]	Blended: Anubumani and Singh [47]		Blended: Mohanty et al. [56]
BTE decrease	Degummed deacidified crude: Leevijit and Prateepchaikul [59], Methyl and ethyl ester of palm oil: Ndayishimiye and Tazerout [61], Biodiesel: Aziz et al. [66]	Crude: Niemi et al. [20], Crude: Niemi et al.[80], Crude: Niemi et al. [18], Blended: Hasib et al. [79], Crude: Niemi et al.[77], Blended: Azad et al.[46]		Blended: Belagur and Reddy [122], Mixed: Bora et al.[125]
Brake Power increase	Blended with additive: Kalam and Masjuki [14]		Methyl ester of waste palm oil: Ozesezen and Canakci [127]	
Brake Power decrease	Blended: Yusaf et al. [60]		Blended: Kalam et al. [49], Used cooking oil biodiesel with additive: Çetinkaya et al. [102], Methyl ester of waste frying oil: Utlu and Koçak [94]	Blended: Sahoo et al. [126]

Table 6
Research findings of different emission constituents for palm, mustard, WCO and *Calophyllum inophyllum* biofuel.

Emissions	Palm oil	Mustard oil	Waste cooking oil	*Calophyllum inophyllum*
EGT increase	Preheated: de Almeida et al. [71], Preheated: Ndayishimiye and Tazerout [61], Kumar et al. [67], Blended: Yusaf et al. [60], Methyl and ethyl ester of palm oil: Ndayishimiye and Tazerout [61]	Blended: Hasib et al. [79]	Blended: Kalam et al. [49]	Blended: Mohanty et al. [56], Blended: Belagur and Reddy [122]
EGT decrease	Degummed deacidified crude: Leevijit and Prateepchaikul [59], Blended: Ndayishimiye and Tazerout [61]		Used cooking oil biodiesel with additive: Çetinkaya et al. [102], Methyl ester of waste frying oil: Utlu and Koçak [94]	Mixed: Bora et al. [125]
Smoke opacity increase				Blended: Belagur and Reddy [122]
Smoke opacity decrease	Degummed deacidified crude: Leevijit and Prateepchaikul [59], Biodiesel: Song et al. [68], Biodiesel: Aziz et al. [66]	Crude: Niemi et al. [20], Crude: Niemi et al. [18], Crude: Niemi et al. [77]	Recycled oil biodiesel: Guo et al. [99], Methyl Ester of waste olive oil: Dorado et al. [103], Methyl ester of waste frying oil: Utlu and Koçak [94], Waste frying palm oil and its blends: Ozesezen and Canakci [48], Methyl ester: Mittelbach et al. [95], Used cooking oil biodiesel: Hamasaki et al. [98], Methyl and Ethyl ester of waste cooking oil: Lapuerta et al. [108], Methyl ester of waste palm oil: Ozesezen and Canakci [127]	Methyl Ester: Venkanna and Reddy [123], Blended: Sahoo et al. [126], Mixed: Bora et al. [125]
CO increase	Preheated: de Almeida et al. [71], Blended: Yusaf et al. [60], Methyl and ethyl ester of palm oil: Ndayishimiye and Tazerout [61], Blended: Ndayishimiye and Tazerout [61], Preheated: Ndayishimiye and Tazerout [61]	Crude: Niemi et al. [20], Crude: Niemi et al. [18], Methyl ester: Bannikov [81], Crude: Niemi et al. [80]		Blended: Mohanty et al. [56], Blended: Belagur and Reddy [122], Blended: Sahoo et al. [126]
CO decrease	Degummed deacidified crude: Leevijit and Prateepchaikul [59], Blended with additive: Kalam and Masjuki [14], Preheated Crude: Kalam and Masjuki [69], Biodiesel: Satyanarayana and Muraleedharan [65]		Blended: Kalam et al.[49], Methyl Ester of waste olive oil: Dorado et al. [103], Methyl ester of waste frying oil: Utlu and Koçak [94], Blended: Lin et al. [93], Waste frying palm oil and its blends: Ozesezen and Canakci [48], Methyl ester: Mittelbach et al. [95]	Methyl Ester: Venkanna and Reddy [123], Mixed: Bora et al. [125]
HC increase	Preheated: de Almeida et al. [71], Blended: Ndayishimiye and Tazerout [61]	Methyl ester: Bannikov [81]		Blended: Mohanty et al. [56], Blended: Belagur and Reddy [122], Methyl Ester: Venkanna and Reddy [123]
HC decrease	Methyl and Ethyl ester: Ndayishimiye and Tazerout [61], Preheated: Ndayishimiye and Tazerout [61], Blended with additive: Kalam and Masjuki [14], Preheated Crude: Kalam and Masjuki [69], Biodiesel: Satyanarayana and Muraleedharan [65]	Crude: Niemi et al. [20], Crude: Niemi et al. [18]	Blended: Kalam et al. [49], Blended: Lin et al. [93], Waste frying palm oil and its blends: Ozesezen and Canakci [48], Methyl ester: Mittelbach et al. [95], Methyl and Ethyl ester of waste cooking oil: Lapuerta et al. [108]	Blended: Sahoo et al. [126], Mixed: Bora et al. [125]
NO_x increase	Degummed deacidified crude: Leevijit and Prateepchaikul [59], Preheated Crude: Kalam and Masjuki [69], Blended: Ndayishimiye and Tazerout [61], Biodiesel: Aziz et al.[66], Biodiesel: Satyanarayana and Muraleedharan [65], Biodiesel: Song et al. [68]		Methyl ester: Mittelbach et al. [95], Blended: Kalam et al. [49], Waste frying palm oil and its blends: Ozesezen and Canakci [48], Waste sunflower oil biodiesel: Usta et al. [106], Methyl ester: Gomez et al. [101]	Blended: Belagur and Reddy [122], Blended: Sahoo et al. [126], Mixed: Bora et al. [125]

NO_x decrease	Blended: Yusaf et al. [60], Preheated: de Almeida et al. [71], Blended with additive: Kalam and Masjuki [14], Methyl and ethyl ester of palm oil: Ndayishimiye and Tazerout [61], Emulsified: Kalam and masjuki [69]	Crude: Niemi et al. [18], Crude: Niemi et al. [20], Methyl ester: Bannikov [81], Crude: Niemi et al.[80], Crude: Niemi et al. [77]	Methyl Ester of waste olive oil: Dorado et al. [103], Methyl ester of waste frying oil: Utlu and Koçak [94]	Blended: Mohanty et al. [56], Methyl Ester: Venkanna and Reddy [123]
CO_2 increase	Preheated: de Almeida et al. [71]		Waste frying palm oil and its blends: Ozesezen and Canakci [48], Waste sunflower oil biodiesel: Usta et al. [106]	
CO_2 decrease			Blended: Kalam et al. [49], Methyl Ester of waste olive oil: Dorado et al. [103], Methyl ester of waste frying oil: Utlu and Koçak [94], Methyl ester of waste palm oil: Ozesezen and Canakci [127]	
PM increase	Emulsified: Kalam and masjuki [69]	Crude: Niemi et al. [18]		
PM decrease	Preheated Crude: Kalam and Masjuki [69], Blended: Lin et al. [64]		Blended: Lin et al. [93], Methyl ester: Mittelbach et al. [95], Yellow grease biodiesel: Canakci and Van Gerpen [97], Used frying oil: Ulusoy and Tekin [104], Methyl and Ethyl ester of waste cooking oil: Lapuerta et al. [108]	

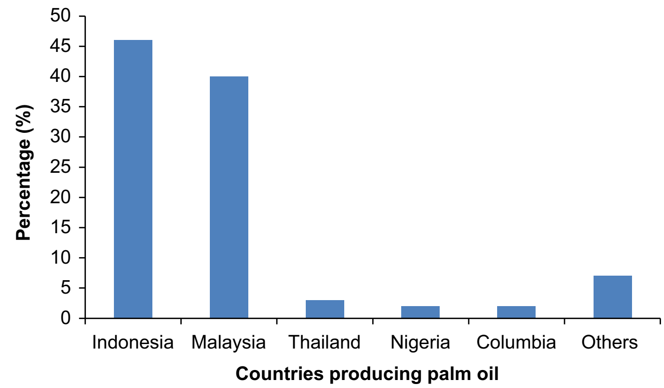

Fig. 2. World palm oil production 2009 [29,30].

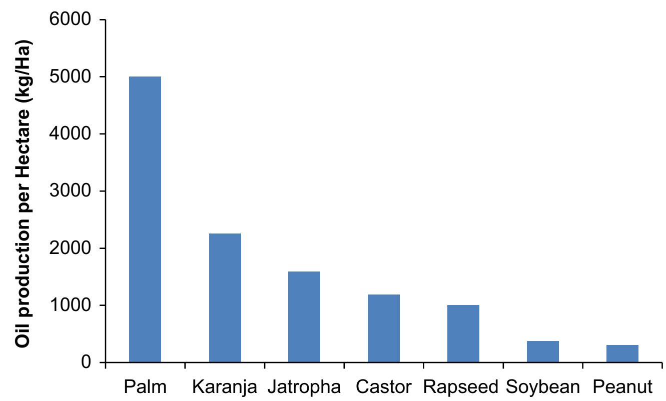

Fig. 3. Comparison of oil production per hectare of palm with other biofuel feedstock [33].

to 20–30 m height [31]. Pinnate leaves can be 3 m to 5 m long and the flowers are densely clustered. Each small flower consists of three sepals and three petals [32].

The oil palms do not spread by offshoots, they are grown by sowing seeds. It takes almost 5–6 months to get matured fruits starting from pollination. Fruit comprises two portions: an oily and fleshy outer layer and a seed inside, which is very rich in oil. Seed is called palm kernel and is surrounded by soft pulp. Each kernel contains 20–21% oil [34]. Fruits are small plum size and grows in heavy bunches of palm trees, each bunch weighing 10–20 kg as shown in Fig. 4. Oil is extracted from both the pulp and the seed. Oil palm trees are commercially cultivated to serve edible oil to the market [35]. Physicochemical properties and fatty acid composition of palm oil biodiesel are given in Tables 1–3.

2.1. Palm oil performance

A research on performance and emission of an indirect injection (IDI) turbocharged automobile diesel engine, operated with degummed de-acidified mixed crude palm oil ($D_{g\text{-}a}$MCPO) was carried out by Leevijit and Prateepchaikul [59]. The author evaluated the performance and emission comparison between ordinary diesel (OD) and D_{g-a}MCPO at three different proportions as 20 vol%, 30 vol% and 40 vol% of blends. This experimental study showed that all blends provide same maximum brake torque corresponding to same maximum brake power at any operating speed ranged from 2000 rpm to 3000 rpm. The more the portion of D_{g-a}MCPO was increased in the biodiesel blend the engine had to supply slightly a higher mass flow rate. The engine work efficiency was satisfactory when operated at high loads of >25 kW. Highest brake thermal efficiency (BTE) and lowest brake

Fig. 4. Palm tree and fruits.

specific fuel consumption (BSFC) were obtained at full load condition. Overall BSFC of the 20 vol%, 30 vol%, 40 vol% blends were higher than OD fuel at about +4.3%, +5.9%, and +7.6%, respectively, while BTEs were lower at about −3.0%, −4.1%, and −5.2%, respectively. Yusaf et al. [60] had similar findings regarding engine torque in a CI engine. At lower speed (below 2000 rpm) using crude palm oil showed higher torque than OD fuel, but at high speed torque was slightly lesser than OD fuel. Generally, when engine is run by 100% biodiesel, fuel consumption was found to be low at lower speed. But BSFC was found higher at low engine speed and better fuel consumption was found at higher engine speed using palm oil blends than OD fuel. Ndayishimiye and Tezerout [61] used preheated palm oil and palm oil blended at 5, 10, 20 and 30% by wt. with diesel to investigate the performance and emission of a Direct Injection (DI) diesel engine. They found BTE of preheated palm oil blends were around 27% higher than OD. But the BSFC were higher at 2–6% for palm oil diesel blends and 14–17% for preheated pure palm oils than OD. Kalam and Masjuki [62] conducted research using palm oil blends with 50 ppm corrosion inhibitor in a diesel engine and found excellent results. Experiments showed 12.4 kW and 11.44 kW maximum brake power obtained from 7.5% to 15% palm oil blends respectively, running at 1600 rpm. Corrosion inhibitor increased fuel conversion from heat energy to work resulting higher brake power. Besides use of Crude Palm Oil (CPO) blends had some adverse effects like heavy carbon deposits inside the engine cylinder, wear of piston rings, uneven spray formation, shorter ignition delay etc. Thus Long term use of CPO may deteriorate engine performance parameters. Bari et al. [63] investigated 500 h cumulative running of diesel engine with CPO which resulted reduced maximum power up to 20% and BSFC was increased up to 26%. Experimental results of Lin et al. [64] also agreed with this higher BSFC and lower power output phenomena using palm oil blends in a diesel generator.

Satyanarayana and Muraleedharan [65] carried out a comparative study by running a four stroke, single cylinder, DI, water cooled, CI engine with OD fuel, palm, rubber-seed and coconut biodiesel. Among all these biodiesels as well as OD fuel, palm biodiesel showed maximum efficiency. Efficiency of OD fuel, palm, coconut and rubber seed biodiesels were found to be 36.19%, 37.78%, 28.04% and 33% respectively at optimum 4.1 kW load. Aziz et al. [66] tested a single cylinder DI diesel engine with palm oil based biodiesels. In their experiments BSFC increased from 0.4% to 3.7% compared to OD fuel, for gradual increase in palm biodiesel blending percentage from 2% to 10% at low and medium speed range. BTE of palm biodiesels were almost same at low speed range but gets lower at high speed range compared to OD fuel which was represented graphically.

2.2. Palm oil emission

Ndayishimiye and Tezerout [61] found Exhaust Gas Temperature (EGT) increases 6–8% more than OD fuel using preheated palm oil which indicates higher ignition delay due to the lower cetane number of blends than OD fuel, at lower speed. Due to the higher viscosity of blends atomization is poor and some unburnt fuels burn in the late combustion phase, resulting lower thermal efficiency and higher EGT [67]. At full load condition Leevijit and Prateepchaikul [59] reported slightly lower EGT than OD fuel. EGT was lowered by −2.7%, −3.0% and −3.4%, respectively for 20 vol%, 30 vol% and 40 vol% palm oil blends than OD fuel. Yusaf et al. [60] found that with the increase of CPO percentage in the blend EGT was increasing. For 25% CPO blend the EGT was comparable to diesel at low speed and lower at high speed range. For 50% CPO, EGT was found higher at low speed range and comparable at high speed range and finally for 75% CPO, EGT was higher than diesel over all speed ranges.

Aziz et al. [66] reported palm biodiesel fuels had lower smoke number than the OD fuel throughout the entire load range. As biodiesel content in the blends increased, smoke was reduced significantly at medium and high load range. The maximum smoke reductions were about 17% and 21% for the engine speeds of 2000 rpm and 2300 rpm, respectively. Song et al. [68] operated a four cylinder, CI diesel engine with palm-olein biodiesel and found less smoke concentration for palm-olein biodiesel compared to OD fuel.

During 100-h of engine operation Kalam and Masjuki [69] found preheated CPO produces lowest level of Carbon monoxide (CO) emissions than OD and emulsified CPO. Preheated CPO contributes to complete combustion which leads to produce less CO than emulsified CPO. Ng and Gan [70] experimented the effect of Exhaust Gas Recirculation (EGR) on CO emission and reported that CO is minimum when EGR is within the .75–.85 range and CO emission further improves with the proportional increase of Palm Oil Methyl Ester (POME). Kalam and Masjuki [14] observed higher amount of CO decreasing phenomenon using corrosion inhibitor. Palm oil blended with corrosion inhibitor decreased CO concentration value even less than 0.01% where maximum acceptable limit is 1%. CO results from incomplete combustion which is reduced at increased load condition. High load condition results in high combustion temperature and better mixing, hence leads more complete combustion. Leevijit and Prateepchaikul [59] reported at full load condition CO emission was significantly lower (about -70%) for 20% palm oil blend than OD fuel. But using 30 vol% and 40 vol% palm oil blend showed similar and slightly higher CO emission trend than OD fuel, respectively. Therefore, 20% blend is suitable considering CO emission. Experiments of Satyanarayana and Muraleedharan [65] revealed palm biodiesel produce less CO than OD fuel and coconut biodiesel. CO emission of OD fuel, coconut and palm biodiesels were 0.055%, 0.039% and 0.023% respectively at full load condition.

Hydro Carbon (HC) emission shows similar trend like CO emission, preheated CPO produces less HC emission than OD fuel [69]. During 350 h operation of a diesel generator by palm oil, de Almeida et al. [71] found HC emission of PO is higher at partial charge but lower at higher percentage of charge than diesel fuel.

Though many studies showed HC formation less than OD fuel at different engine conditions using palm oil, higher viscosity and lower cetane number of palm oil results some unavoidable HC emissions [72]. Palm biodiesel showed a high amount of HC reduction in the experiments of Satyanarayana and Muraleedharan [65]. HC emission for OD fuel was found to be 120 ppm and for palm biodiesel it was 72 ppm, which means a 40% reduction of HC emission.

Many researchers have found different factors influencing NO_x level. NO_x level increases with the increase of combustion temperature. It was seen that NO_x level decreases with increase of palm oil percentage in the blend. Masjuki et al. [73] reported, increasing amount of palm oil blend lowers heat release at premix combustion phase and results lower peak combustion temperature inside engine cylinder. Thus, NO_x level decreases from 147 ppm to 135 ppm while palm oil blend raised from 7.5% to 15%. According to Graboski and Cornimik [74], NO_x emission is a function of speed and load. Kalam and Masjuki [69] used emulsified palm oil which helped to reduce NO_x level. With the increase of only 2% water in CPO, the NO_x level decreased from 179 ppm to 174 ppm at 100th hour of engine operation. Experimental results of Leevijit and prateepchaikul [59] clearly indicated that NO_x increases with increasing loads in CI engine. Rich fuel supply created larger flame zones stimulating combustion temperature, hence increased NO_x. In comparison to diesel they also found higher NO_x emission using 20 vol% palm oil blend. Aziz et al. [66] found NO_x emission increased with the increase of biodiesel percentage in the blend and with the increase of load compared to OD fuel. Highest NO_x increase for palm biodiesel was about 14% and 16% at 2000 rpm and 2300 rpm, respectively. Satyanarayana and Muraleedharan [65] found a 7.4% increase in NO_x emission for palm biodiesel compared to OD fuel. In amount it was 578 ppm and 538 ppm for palm biodiesel and OD fuel, respectively. Song et al. [68] found palm-olein biodiesel produces more smoke concentration than that of OD fuel.

Experiments of De Almeida et al. [71] revealed almost same O_2 and CO_2 emission percentage compared to the diesel fuel and showed same trend with varying charge. It was found by many researchers that CO_2 emission is reduced by using palm oil [26]. Experimental results of Yusaf et al. [60] showed 2.8–19.7 kg CO_2 equivalent per kg of palm oil. For 25 and 50% CPO blends O_2 content was higher than OD fuel at speed above 2000 rpm. Besides exhaust gas contains lower O_2 content compared to OD fuel at all speeds using 75% diesel fuel. Though Presence of oxygen indicates complete combustion, however due to imperfect air-fuel mixture there is always some possibilities of oxygen presence in the emission.

Experimental study of Lin et al. [64] showed PM emission of 10, 20 and 30% palm oil blends are less than that of pure diesel but larger in case of 50%, 75% blends and pure oil. After running a diesel engine, Kalam and Masjuki [69] measured PM at 30th hour and 100th hour of operation for OD and preheated CPO. Results were 0.60 g/kW h and 0.51 g/kW h at 30th hour, and 0.77 g/kW h and 0.70 g/kW h at 100th hour for OD fuel and CPO, respectively.

3. Mustard oil

Wild mustard belongs to the Brassicaceae family and also known as field mustard. The Brassicacea plant family is a very rich source of many important biodiesel feedstock. *Brassica alba* L., *Camelina sativa* L., *Brassica carinata* L., *Brassica napus* L., *Paphanus sativus* L. oils are some recently reported potential feedstock of this plant family. Among them Canola or Rapseed (*Brassica napus* L.) has gained widespread acceptance as a common commodity feedstock for biodiesel production [75].

Wild mustard (*Brassica juncea* L.) have high yield potential for producing biodiesel, especially when cultivated in humid, dry and hot weathers like Bangladesh, India and Pakistan [45]. Morphologically wild mustard has been identified as *Sinapsis arvensis* L. Intensive research is going on currently to improve its productivity. Besides commercial cultivation, mustard plant also abundantly grows in orchard, plantation crops, waste lands and along roadside. Canada is one of the major producer of winter mustard and winter canola. Winter mustard is also cultivated in northern latitudes of United States such as Washington, North Dakota, Idaho and Montana. Recently, in Australia, Indian mustard (*B. juncea* L.) has been introduced as a short season oil seed crop in the cropping regions where rainfall is low [76].

Mustard seed plant is an annual herbaceous plant and can grow from two to eight feet tall with small yellow flowers as shown in Fig. 5. [75]. Each flower have four petals up to 1/3 in. across and green leaves are covered in small hairs. These yellow flowers produce hairy seed pods. Each pod contains around a half dozen seeds. Just before these pods become ripe and bursting, seeds are harvested. Seeds are hard round and usually around 1 mm to 1.5 mm in diameter with a color ranging from yellow to light brown. Oil is extracted by pressing these seeds and a crop yield of around 1200 kg/ha (500 kg/ac) is a realistic harvest in Finland. Around 300 L of mustard oil can be obtained from 1200 kg of seed [18]. The energy content of oil is four times the energy consumed to produce oil which means production to fuel energy ratio is 4.0. Zheljazkov et al. [19] found mustard oil yields would provide 590–875 kg biodiesel oil per ha. As the cost of pressing device in oil production is very low mustard seed oil can be produced at a cost comparable with untaxed diesel fuel and appears to be an economically acceptable feedstock for biodiesel production [77]. Physicochemical properties and fatty acid composition of mustard biodiesel are given in Tables 1 and 3.

3.1. Mustard oil performance

Biodiesel produced from mustard oil through trans-esterification can be successfully used in diesel engine but optimum performance might be deviated slightly [45,78,79]. In practical case a farmer of south western finland operated his tractor engine with his own non-esterified cold pressed mustard seed oil for more than eight years which inspired Niemi et al. [18] to conduct in depth research on emission and performance on a intercooled, turbo charged, DI tractor diesel engine. Experiments showed BTE of mustard seed oil (MSO) is very similar to diesel fuel. At 1800 rpm same 42% BTE was obtained and at highest speed slightly lower BTE was obtained compared to OD fuel. Overall efficiency did not varied more than 2.5% compared to OD fuel. BMEP of mustard seed oil was 11.9 bar and for OD fuel it was 11.5 bar while running at full load condition [20,80]. Different injection timing also brought no significant change in the performance. Heat release rate and intake pressure were also similar but faster burning occurred. Almost same break torque was obtained by advancing injection timing 17° and 19° and highest BMEP value was 11.4 bar [77]. Anbumani and Singh [47] experimented with different blending ratios of mustard and neem biodiesel in C.I. engine and found mustard oil at 20% blend performs best among them. Basically mustard oil was used in esterified butyl ester form and its 20% blend with diesel satisfies ASTM standard properties for biodiesel. Specific fuel consumption was slightly decreased (0.135 kJ/kW-h to 0.045 kJ/kW-h) due to better fuel combustion. BTE showed increasing trend up to 16 kg load level and started to decrease beyond that level. Rattan and Kumar [78] experimented with 20%, 30% and 50% mustard oil blended with diesel and found BSFC is inversely proportional to load. By studying lubricating oil temperature they suggested SAE-30 lubricant is suitable. Specific fuel consumption increases with the percentage increase of mustard oil blends. Azad et al. [46] and Hasib et al. [79] had similar

findings regarding BSFC. From graphical representation they clearly showed that crude biofuel blends gives lower BSFC than that of transesterified one and it is inversely proportional to thermal efficiency. Regarding overall thermal efficiency, 20% mustard oil blend and regarding maximum thermal efficiency, 30% mustard oil blend performed best. Bannikov [45] conducted his research on a direct injection diesel engine using mustard oil methyl ester as fuel and found 15% increase of BSFC and 3% reduction of brake fuel conversion efficiency compared to diesel fuel while mechanical efficiency was unchanged. Hasib et al. [79] concluded that poor atomization and lower heating value than diesel fuel are responsible for high BSFC and low BTE of mustard oil than diesel fuel.

3.2. Mustard oil emission

Bannikov [45] reported EGT of diesel engine remains unchanged using mustard methyl ester. Hasib et al. [79] found different findings regarding EGT. Among different mustard oil blends they found that except 30% and 40% blends, all others result in higher EGT than that of OD fuel. But 30% and 40% both blends showed lower EGT than OD fuel at higher load condition.

Regarding smoke content mustard oil is favourable over OD fuel [20]. Smoke varied from 0.2 to 2.4 Bosch number for mustard oil and varied 1.3–3.7 Bosch number for OD fuel. High oxygen content is responsible for this reduced smoke generation. According to Anbumani et al. [47] smoke intensity showed no significant variation, however 20% mustard oil blend resulted less smoke intensity compared to other blends. About 40% decrease of exhaust opacity than diesel fuel was reported by Bannikov [45] at all loads using mustard methyl ester and same exhaust opacity for both mustard and OD fuel at rated speed.

According to Niemi et al. [20] at high load range MSO produced less CO but at low load range produced more CO than diesel fuel. Similar results were achieved in their previous tests [18,77]. When the engine is in idling condition, MSO emitted 550 ppm and OD fuel emitted 300 ppm of CO. Engine complied ISO 8178-4/C1 standard for CO emission limit successfully [80]. Some contradictory result was found by Bannikov that CO was increased by 25% at full load condition than OD fuel [45,81]. Thus, regarding CO emission diesel oil is favourable at low load and mustard oil is favourable at high load condition [82].

Bannikov [45] found slight variation in overall hydrocarbon emission compared to diesel fuel, using mustard methyl ester. Some researchers found HC emission was low in case of MSO compared to OD fuel but no strong conclusion can be made from this finding. Thus Niemi et al. [77,80] measured several HC components separately by using FT-IR. Acetylene contents were varied from 1 ppm to 4 ppm and benzene contents were varied from 0 ppm to 1.8 ppm during retarded ignition timing. Even at idling condition only 0.9 ppm aromatic HC was recorded at its highest level. Aldehyde contents were higher in case of MSO than OD fuel. Some indication suggested ignition timing retardation may reduce alcohol emission but overall alcohol emission of mustard oil was slightly higher than that of OD fuel. For both diesel and mustard seed oil only a very small amount of methane was found which remained constant against load. FT-IR results showed higher methane emission than gas chromatography analysis [83]. Irregular olefin emission was found in case of mustard oil and no olefins were found in the exhaust while using diesel. Thus, Niemi et al. [77] summarised that aldehydes, aromatics, acetylene, alcohols and non-methane paraffins were lower and olefins emission was higher with MSO than OD fuel. Non-methane paraffins emission also resulted no significant comparative changes, 0.74 ppm was the highest amount recorded [80]. Bannikov [45] found slight overall hydrocarbon variation using mustard methyl ester compared to diesel fuel.

Experiments performed by Niemi et al. [18,20,77] showed reduction of NO_x emission at all loads by using MSO and which is also supported by Bannikov [45]. Retardation of injection timing reduced it further. At high load range MSO and OD fuel both produced almost same amount of NO_x. At middle load range amount of NO_x was considerably low and at low speed range it was remarkably low in case of MSO than OD fuel. At idling condition, wet exhaust NO_x content was 360 ppm for diesel fuel whereas it was 160 ppm for MSO. Bannikov [45] also supported that NO_x emission decreased at all loads compared to OD fuel while running the engine with mustard oil methyl ester. So if NO_x emission is considered, MSO is superior than diesel fuel [80].

After 154 h of operation performed by Niemi et al. [80] it can be said that combustion and mixture formation of MSO were satisfactory as NO_x, Smoke and CO emission were low. However at low

Fig. 5. Mustard plant and seed.

idling condition, performance of MSO was not satisfactory. Results of these studies of using mustard seed oil differs from those reported in [72],[84] and [85] who conducted research on rapeseed oil, another plant of Brassica family. They found more CO, NO_x, CO_2 emission than OD fuel which may strengthen the appropriateness of using mustard oil as biofuel.

4. Waste cooking oil (WCO)

Frying oil used for cooking at high temperatures and edible fat mixed in kitchen waste are the main sources of WCO [86]. A large amount of waste cooking oil is generated every day in the world from households, restaurants, food processing industries and fast food shops. According to the estimation of Energy Information Administration around 100 million gallons of waste cooking oil is produced per day in USA, where the average per capita waste cooking oil was reported to be 9 pounds [87]. In Japan, nearly 0.4–0.6 million tons of WCO are generated annually [88]. Quantities of WCO produced per year in various countries of the world is presented in Fig. 6. WCO is also used as oil additive for fodder preparation and soap manufacturing. Disposal of WCO and fats has become a serious environmental problem around the world. Proper utilization and management of WCO can effectively solve this problem [34].

As using edible oil to produce biodiesel, at the expense of food security is highly criticized by several non-governmental organisations, WCO is considered as the most feasible feedstock of biodiesel, apart from some drawbacks like high fatty acid and water content. Physical and chemical properties and fatty acid composition of WCO are given in Tables 1 and 3. Besides, use of WCO significantly reduces total biodiesel processing cost as the cost of WCO is 2 to 3 times less than that of vegetable oil. Comparison of average price of WCO with other biofuel is showed in Fig. 7.

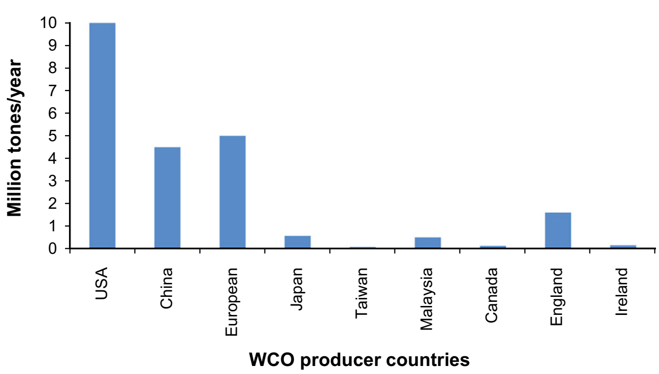

Fig. 6. Quantities of WCO produced per year in various countries of the world [39].

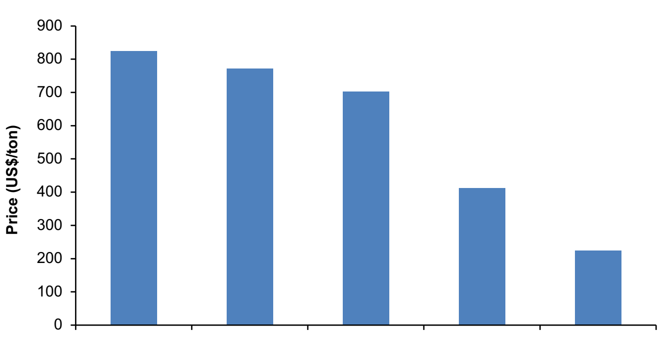

Fig. 7. Comparison of average price of WCO with other biofuel [39].

Fig.8. Different waste cooking oil.

Though source of cooking oil differs across the globe, plant based lipids such as sunflower oil, corn oil, coconut oil, palm oil, olive oil, soybean oil, canola oil, rapeseed oil margarine etc. are the main feedstock. Animal based lipids such as fish oil, ghee, butter etc. used for cooking and frying are also some potential sources of WCO. In Iran, a successful work on using waste fish oil was also published by Yahyaee et al. [89]. Different WCO are showed in Fig. 8. Biodiesel is produced through the transesterification of these lipids [39]. Physicochemical properties and fatty acid composition of WCO biodiesel are given in Tables 1 and 3.

4.1. Waste cooking oil performance

While conducting research on biodiesel, trans-esterified from WCO, most of the researchers found slightly poor thermal performance and higher BSFC than OD fuel [90].

Ozsezen and Canakci [48] investigated an unmodified IDI diesel engine fueled with esterified waste frying palm oil. Slight increase of BSFC and reduction of break torque was found due to low energy content and around 9.8% lower heating value of WCO biodiesel compared to diesel fuel. In another work, Canakci et al. [91] used neural network and found that BSFC increases with the increase in biodiesel percentage in the blends. BTE and brake torque were also reduced from their predicted values with the increasing amount of WCO in the biodiesel blends. Experiments of Sharon et al. [92] established this finding while a DI diesel engine was fueled with methyl ester of used palm oil. Obtained BTE of 25% and 50% blends of used palm oil biodiesel were almost same as obtained for OD fuel. BTE of diesel, 25%, 50%, 75% and 100% biodiesel blends were 30.895%, 30.56%, 29.22%, 29.58% and 28.65%, respectively. BSFC of diesel and 100% biodiesel were 274.90 g/kW h and 314.91 g/kW h at full load condition. BSFC of 25%, 50%, and 75% biodiesel were observed to be higher by 2.59%, 8.93% and 9.25% than OD fuel, respectively.

Lin et al. [93] tested WCO blended at different percentages with ultra-low sulfur diesel (ULSD) in a heavy duty diesel engine. Experiments showed 0.136%, 0.562%, 1.10% and 2.29% increase of BSFC for 5%, 10%, 20% and 30% WCO blended ULSD respectively compared to pure ULSD. They also commented that the BSFC increase is the consequence of lower heating value of biodiesel blends than ULSD.

Kalam et al. [49] carried out experimental study on 5% blend of waste palm oil and coconut oil in an unmodified IDI engine. At 3000 rpm maximum brake power were 36.7 kW, 36.10 kW and 36.20 kW for diesel fuel, 5% waste coconut oil and 5% waste palm oil blends, respectively. In comparison with OD fuel, 0.7% and 1.2% reduction of brake power were found for 5% blend of coconut and palm WCO respectively on an average.

Utlu and Koçak [94] found 14.34% increase of BSFC and 4.3% and 4.5% average reduction of average torque and average power respectively than OD fuel, using waste frying oil methyl ester (WFOME) in a DI diesel engine.

Mittelbach et al. [95] replaced diesel fuel totally by WFOME in a four stroke, turbocharged, direct injection diesel engine and observed 4% increase in fuel consumption at fully loaded condition and similar fuel consumption was observed at normal operating condition compared to OD fuel.

Engine performance test was carried out by Sudhir et al. [96] on a naturally aspirated, four stroke, DI diesel engine using WCO biodiesel. Results showed thermal performance of WCO biodiesel is closely resembled with OD fuel and fresh oil biodiesel. Compared to diesel fuel marginally poorer performance of WCO biodiesel was found only at part load conditions. Only 1–1.5% BTE loss for WCO biodiesel than OD fuel was reported at full load condition.

Canakci and Van Gerpen [97] found no significant variations in BTE among different blends of WCO in a 57 kW diesel engine. Only a 2.5% increase of BSFC was found compared to diesel fuel using 20% blend of WCO biodiesel.

Hamasaki et al. [98] investigated performance of three WCO biodiesel of different acid values in a single cylinder diesel engine and reported similar BTE in all cases.

A linear decreasing relationship between biodiesel percentage and maximum engine power was found by Guo et al. [99] while using recycled oil in a four cylinder, four stroke, water cooled diesel engine. Power variation was small for all tested biodiesels. Only a 6% power reduction was found by using 100% biodiesel compared to OD fuel.

Waste palm oil ethyl ester (WPOEE) was investigated by Al-Widyan et al. [100] in a single cylinder direct injection diesel engine. By studying blends of different percentage it was revealed that 75% blend and pure WPOEE performed best in overall consideration. These two blends steadily performed over the whole speed range in terms of BSFC, BTE and maximum brake power.

Approximately 9% reduction of brake power is found by using WCO biodiesel in comparison with OD fuel in the experiments performed by Gonzalez-Gomez et al. [101] while investigating a 2 L Toyota diesel van. Similar findings were reported by the experiments performed by Çetinkaya et al. [102] by using WCO originated biodiesel in a four cylinder, four stroke diesel engine. They obtained 3–5% less torque and break power compared to OD fuel. Lower specific value of the biodiesel was reported as the reason of this difference. Fuel consumption was found very similar with OD fuel and high oxygen content of biodiesel may be the probable cause of this phenomena.

Dorado et al. [103] carried out research on exhaust emissions from a three cylinder, four stroke, water cooled DI Perkins diesel engine fueled with waste olive oil methyl ester. A slight increase of BSFC (though less than 8.5%) was observed which can be tolerated due to the benefits in emission. Statistical analysis showed no significant change in thermal performance and no noticeable change in operation was found.

On contrary some researchers also found even better thermal performance over OD fuel while using WCO. Ulusoy and Tekin [104] measured engine performance by using waste frying oil and showed 2.03% and 3.35% reduction of wheel power and wheel force, respectively. Acceleration test was also performed and 7.32% and 8.78% reduction of wheel power were found during 40–100 km/h and 60–100 km/h of acceleration periods, respectively. Fuel consumption of used frying oil biodiesel was 2.43% less than diesel fuel as a result of reduction of wheel power and wheel force. So, when reduction of wheel power and force were considered, results were satisfactory.

4.2. Waste cooking oil emission

WCO-biofuel significantly reduces most of the harmful emissions. Utlu and Koçak [94] showed 539 °C and 499 °C EGT for diesel and WFOME respectively at 3500 rpm engine speed while maximum power was obtained. In percentage it was 6.35% reduction in EGT which might be the result of lower heating value of WFOME. Roskilly et al. [105] tested recycled cooking fat biodiesel and diesel fuel in Nanni diesel 3.100HE and Perkins 404C-22 engines. For Nanni engine, exhaust temperatures were around 1.8 to 11.5% higher for WCO than diesel fuel and it was very much similar in case of Perkins engine as 2% differences in EGT between WCO and diesel fuel were observed in this case. Çetinkaya et al. [102] reported less EGT than OD fuel at all engine speed over 1500 rpm to 4500 rpm speed range, using WCO biodiesel. It indicates good burning quality of biodiesel inside the cylinder which is the result of high O_2 content of used cooking oil. According to Kalam et al. [49] EGT decreased 1.42% and 1.58% by using waste palm oil and waste coconut oil respectively, compared to diesel fuel.

Smoke opacity was found to be reduced almost at all cases when used frying oil biodiesel and blends were used. Guo et al. [99] observed a maximum 83% reduction of smoke opacity by using recycled oil biodiesels. Similar findings were also found by Hamasaki et al. [98]. According to Utlu and Koçak [94] smoke density were measured to be 51.5% and 34.8% at 4000 rpm for diesel fuel and WFOME, respectively. On an average percentage it was a reduction of 22.46% compared to diesel fuel. Smoke emission was visually observed by Dorado et al. [103] and amount was extremely low. However, as they used waste olive oil the exhaust gas had a different smell of slightly fried food.

Utlu and Koçak [94] revealed about 17.13% CO reduction on an average for WCO biodiesel than OD fuel. In amount maximum CO emission was 876 ppm for OD fuel and 665 ppm for WFOME at 1750 rpm. Dorado et al. [103] found more significant amount of CO reduction than generally obtained by using WCO biodiesel. Around 58.9% CO can be reduced by using waste olive oil. Usta et al. [106] showed CO emission inversely proportional to engine speed. Here experiments were carried out by using waste sunflower oil and its blends with OD fuel. However, no significant change in CO was found at partially loaded condition of the diesel engine. Kalam et al. [49] found CO was reduced by 7.3% for waste coconut oil and 21% for waste palm oil than that of OD fuel.

Experiments showed less HC emission compared to OD fuel by using WCO [95,107,108]. As a result of WCO biodiesel use, around 30.66% decrease in HC emission was showed by Ulusoy and Tekin [104]. An YC6M220G turbocharged diesel engine exhaust emissions were measured by Meng et al. [109] and 26.7% reduction of HC was found than diesel fuel by using 20% blend of WCO biodiesel. A sharp reduction of total HC emission was found in the research carried out by Lapuerta et al. [110] while testing a diesel engine. Guo et al. [99] also reported less HC emission for different blending percentages of recycled oil biodiesels than the neat petroleum diesel.

Due to high oxygen content of WCO and higher combustion temperature most of the carried out experiments revealed increase of NO_x emissions than OD fuel [95,101,104,106]. But this trend slowed down with decreasing load. A single cylinder engine powered by three different biodiesels of used cooking oil containing different acid values was tested by Hamasaki et al. [98] and NO_x emissions were found to be decreased slightly at low loads and increased at high loads compared to OD fuel. Lin et al. [111] used WCO, WCO biodiesel/blends and OD fuel to test a four cylinder, four stroke, 2.2 L pre-combustion diesel engine. Higher NO_x emission at various engine speeds were obtained by WCO biodiesel compared to diesel fuel. Results of some researchers also

showed NO_x decreasing phenomenon by using WCO biodiesel. When speed range was between maximum torque and maximum power, Utlu and Koçak [94] reported that increase in NO_x emission depends on the rising of volumetric efficiencies and EGT. Variation of NO_x was represented with respect to engine speed. At 3000 rpm, it was 465 ppm for WFOME and 482 ppm for OD fuel. So, in this case NO_x emission decreased. Another NO_x decreasing phenomenon (up to 32%) was presented by Dorado et al. [103] due to 17.6% increase of oxygen concentration. It also should be noted that they used waste olive oil for the first time and results can be different from using ordinary WCO biodiesel. However, NO_2 emission was increased and the amount was quite high compared to NO emission. Kalam et al. [41] investigated NO_x emission of WCO biodiesel blends and observed post-flame gases contain maximum amount of NO_x rather than flame–front gases. On an average amount of NO_x emission were 237 ppm, 235 ppm and 242 ppm for OD fuel, 5% waste coconut oil blend, and 5% waste palm oil blend, respectively. In percentage, waste coconut oil blend reduced 1% and waste palm oil blend reduced 2% of NO_x emission than diesel fuel, respectively.

Experiments of Utlu and Koçak [94] revealed Amount of CO_2 was reduced by 8.05% on an average for WFOME than that of OD fuel, in amount it was 0.4ppm reduced at 3500 rpm. Dorado et al. [103] found 8.6% CO_2 can be reduced by using waste olive oil. Usta et al. [106] showed higher CO_2 emission at full load compared to diesel fuel. Here experiments were carried out by using waste sunflower oil and its blends with OD fuel. Kalam et al. [38] found 7.94%, 8.05% and 7.89% CO_2 production from OD fuel, waste coconut oil and waste palm oil respectively, which showed waste palm oil produced less CO_2 than OD fuel and waste coconut oil.

Transesterified WCO performs better regarding PM emission. In experiments performed by Mittelbach et al. [95] a four stroke, four cylinder, turbocharged, DI diesel engine with EGR was powered by WCO ethyl ester. Results showed significant reduction of PM compared to diesel fuel. Similar findings were found by Canakci and Van Gerpen [97] where a 65% reduction of PM emission was achieved by using WCO biodiesel. A study was conducted by Lapuerta et al. [112] in a four stroke, four cylinder, intercooled, turbocharged DI diesel engine powered by WCO showed a sharp decrease in PM emission and observed that mean particle size was reducing with increasing biodiesel concentration.

5. *Calophyllum inophyllum* oil

C. inophyllum L. belongs to the Clusiaceae (formerly Guttiferae) plant family and found in shorelines and warm coastal areas across the Pacific and Indian oceans [113,114]. Scientific name *Calophyllum* is a Greek word means “beautiful leaf” and *inophyllum* refers to the straight lines made by the veins in the leaves. *C. inophyllum* is native to tropical shorelines across Indian and pacific oceans, from Madagascar to Tahiti and Marquesas island. It was first found in Northern Marianas Island at north and the Ryukyu islands in southern Japan at south and westward throughout Polynesia [115]. Different vernacular names of *C. inophyllumin* various countries of the world are shown in Table 4.

C. inophyllum is a large tree, usually grows 12–20 m, (40–65 ft) in height. Open grown trees can become wider than height, often leaning with broad and spreading crowns. The bark is grey with flat ridges and sap is milky white and sticky. *C. inophyllum* leaves are glossy and heavy, oval shaped with rounded tips [118]. Leaves are 10–20 cm (4–8 in) long and 6–9 cm (2.4–3.6 in.) wide. Young leaves are light green and old leaves are dark green in colour. *C. inophyllum* flowers are white with yellow stamens, blooms on long stalks in leaf axils. Around 4–15 flowers are borne in a cluster. Young fruits are like round green balls and around 2–5 cm (0.8–2 in.) in diameter. Matured fruits are yellow in colour and wrinkled when ripe. A single seed kernel is surrounded by a thin inner layer and this layer is surrounded by a hard shell as shown in Fig. 9.

Kernels of *C. inophyllum* have a very high oil content (75%) and most of them (71%) are unsaturated oleic and linoleic acid [119]. Physio-chemical properties and fatty acid composition of

Fig. 9. *Calophyllum inophyllum* plant and seed [114].

C. inophyllum is given in Tables 1 and 3, respectively. Fruits are usually born twice a year, in April–June and again in October–December. Once grown, a *C. inophyllum* tree produces up to 100 kg fruits and about 18 kg oil. There are about 100–200 fruits/kg in shell with the skin and pulp removed [120].

5.1. Calophyllum inophyllum oil performance

Sahoo et al. [121] evaluated performance of neat 100% (CB100), 50% (CB50) and 20% (CB20) *C. inophyllum* biodiesel blends in a CI tractor engine. All important performance parameters were evaluated and compared with OD fuel and different blends of Jatropha and Karanja biodiesels. For CB20 and CB50, fuel economy was improved compared to OD fuel. On an average, measured fuel economy for CB20, CB50 and CB100 was 180.55 g/bhp-h, 181.15 g/bhp-h and 189.97 g/bhp-h respectively at rated speed. At low speed range of 1200 rpm to 1400 rpm no significant change in power was observed using biodiesel blends but a slight power reduction was obtained for CB20 and CB100. Maximum power was decreased by 1.93% compared to OD fuel for CB20 over the entire speed range. In case of CB50 an improvement in power from 0.19% to 0.88% was obtained. But for CB100, no power improvement trend was observed. Brake specific energy consumption (BSEC) decreased with the increase of blending percentage and BSEC increased with the speed. BSEC was deteriorated for all biodiesels but among karanja, jatropha and *C. inophyllum* blends, CB20 was suggested to be the best one as BSEC deterioration was minimum (2.59%). CB20 was recommended as the optimum fuel blend.

Belagur and Reddy [122] operated a DI diesel engine with neat diesel and a 50% blend of *C. inophyllum* with 50% diesel fuel. Rate of injection and ignition delay was controlled by changing plunger diameter (PD). Higher BTE was resulted from the dominance of premixed combustion phase assisted by the increase of injection rate as well as PD. BTE were plotted with respect to load for various PD. Considering obtained BTE, 8 mm and 9 mm PD were found to be the best for OD fuel and *C. inophyllum* blends, respectively.

Venkanna and Reddy [123] investigated a DI diesel engine fueled with *C. inophyllum* oil methyl ester (COME) and OD fuel at various injector opening pressure (IOP) ranged from 200 bar to 260 bar. It was observed from the graph that the BSFC of COME decreased as IOP increased. BTE was increased gradually with the increase of load. BSFC was slightly higher and BTE was slightly lower than OD fuel using COME. At 25% load, decrease in BTE was 7.67% and increase in BSFC was 20.73% at 50% load, decrease in BTE was 5.56% and increase in BSFC was 17.92%, at 75% load decrease in BTE was 1.94% and increase in BSFC was 13.54%, and at 100% load, decrease in BTE was 4.11% and increase in BSFC was 16.18% using COME compared to OD fuel. Best performances for COME regarding BSFC were found at 75% and 100% load with IOP 260 bar.

Bora et al. [124] investigated performance and emission of a CI engine with neat *C. inophyllum* (C100), koroch and jatropha biofuel and compared with biodiesel obtained from mixing of these feed stocks (BOMF). BSFC showed a decreasing trend with increasing load and BSFC of C100 was found 2.06% higher than BOMF. Thermal efficiency of C100 was 2.2% higher than karanja biodiesel and 0.61% lower than BOMF. In another set of experiments, Bora et al. [125] used a mixture of *C. inophyllum*, karanja and jatropha oil with OD fuel and measured performance and emissions of a diesel engine. BSFC and thermal efficiency decreased slightly than OD fuel at all loads for biodiesel. Due to lower heating value of biodiesel, higher blending was needed to produce same amount of energy compared to OD fuel.

Mohanty et al. [56] blended 10% (C10), 30% (C30) and 50% (C50) *C. inophyllum* oil with OD fuel on a volumetric basis to run a diesel engine and investigated combustion, performance and emission. At fully loaded condition experiments showed 28.96%, 28.73% and 28.28% BTE for C10, C30 and C50 biodiesel blends respectively while it was 28.6% for OD fuel. As fuel consumption for blends of two different fuels having different heating values are not reliable enough, BSEC was measured instead of measuring BSFC. Variation of BSEC with load showed less BSEC requirement for C10 and C30 biodiesel blends compared to OD fuel.

5.2. Calophyllum inophyllum oil emission

EGT of *C. inophyllum* biodiesel blends are found very similar and sometimes slightly higher compared to OD fuel found by many researchers. Mohanty et al. [56] found EGT rises from 160 °C to 380 °C at no load and full load condition respectively for C50 and EGT rises from 140 °C to 300 °C at no load and full load condition respectively for C30. These values of EGT are slightly higher than that of OD fuel. Experiments of Belagur and Reddy [122] showed EGT using 50% Calophyllum biodiesel blend were almost same for all PD and were higher than OD fuel. As almost same amount of fuel was consumed per hour, Bora et al. [124,125] found similar EGT for mixed *C. inphyllum* biodiesel and OD fuel and EGT increased with increasing load.

Sahoo et al. [126] found smoke opacity of CB20, CB50 and CB100 at full throttle position were 29.22%, 44.15% and 69.48% less than diesel fuel respectively at rated speed and comparatively these values were even less than karanja and jatropha biodiesel blends. At part throttle position and rated speed smoke emission for CB20, CB50 and CB100 were 1.19, 1.04 and 1.32 Bosch respectively and amount of smoke emission for CB100 was 1/9th of that of OD fuel. Venkanna and Reddy [123] reported 11%–20% reduction of smoke opacity compared to OD fuel by using COME at light load operation. At medium and high load, smoke opacity increased rapidly for COME but in fact remains lower than OD fuel. Smoke emissions of Calophyllum biodiesel blend were found less than OD fuel in all cases and least value was observed at 10 mm PD [122].

Experiments of Venkanna and Reddy [123] revealed lower CO emission than OD fuel while using COME and this scenario was improved more, when blended biodiesel was used. Better combustion was obtained at higher injection rate which leads to higher injection pressure and satisfactory spray formation, hence reducing CO emission. Graphical representation of CO versus load showed that CO emission using COME remains almost invariable throughout the entire load range, while it gets towards more danger region in case of OD fuel. Injector opening pressure also influenced these emission characteristics and it was quite difficult to sort out reliable mutual dependency and further research is needed. CO emission was lower for 10 mm than 8 mm PD using CB50. Bora et al. [125] also reported similar findings regarding CO reduction when Calophyllum oil is used with other mixed non-edible oils. However, CO emission was not always reduced using *C. inophyllum* biodiesels and sometimes, it shows dependency on blending ratios. Experiments performed by Sahoo et al. [126] showed 1.75 g/kW h, 1.32 g/kW h and 1.12 g/kW h of cumulative CO emission for CB20, CB50 and CB100, respectively. In percentage, CO emission was −12.96%, 34.24% and 2.59% more compared to OD fuel for CB100, CB20 and CB50, respectively. Graphical comparison of different biodiesel blends and OD fuel revealed CB100 as the optimum fuel regarding CO emission. Experiments of Mohanty et al. [56] showed CO emission for OD fuel was less than C10, C30 and C50 which was an indication of incomplete combustion using biodiesel.

Sahoo et al. [126] found *C. inophyllum* biodiesel stands as the better solution than OD fuel and other biodiesel blends regarding HC emission. Total HC reduction for CB20, CB50 and CB100 were 6.84%, 2.73% and 6.75% respectively compared to OD fuel. Therefore, CB20 was the optimized solution regarding HC emission

according to experimental results. Some researchers reported more HC emission for Calophyllum blends than OD fuel [56,123]. According to Mohanty et al. [56] 3–5 ppm lesser HC emission was found by OD fuel than *C. inophyllum* blends. Among C10, C30 and C50 blends, C30 resulted in more complete combustion and less HC emission than OD fuel. Venkanna and Reddy [123] also reported a general tendency of increasing HC emission by using COME. A clear increasing trend of HC emission with the increase of load was represented graphically.

NO_x emission increases with the increase of temperature and pressure inside the cylinder which depends on PD and other operating conditions. Belagur and Reddy [122] showed NO_x emission increases with the increase of PD and highest amount was obtained at 10 mm PD using C50. OD fuel and Calophyllum oil blends were tested under same operating conditions and PD. At 10 mm PD, OD fuel resulted enormously high temperature. Hence, from graphical representation it was clear that about 20 ppm more NO_x than C50 at all load conditions was produced by OD fuel. However, experiments of Sahoo et al. [126] revealed 14.87%, 17.31% and 22.5% increase in NO_x emission for CB20, CB50 and CB100 respectively compared to OD fuel. Investigations of Bora et al. [124] revealed that amount of NO_x increases with increasing the percentage of *C. inophyllum* oil in the blend. NO_x emission from C20 was nearly same as OD fuel and NO_x emission showed decreasing trend with increasing BMEP. Though NO_x emission generally increases for biofuel, Some exceptional results were found by Mohanty et al. [56] where NO_x emission was lower than OD fuel using C10, and C50 except for C30. According to them, higher cetane number and lower heating value of C10 and C50 contributed to lower NO_x emission.

6. Summary of emission and performance of biofuel

This review discussed four biofuels from both edible and non-edible sources having different physicochemical properties. Since physicochemical properties of biofuel vary according to the quality of feedstock, adopted transesterification process, storage time, operating conditions and engine features, therefore experiments carried out by different researcher revealed different results regarding engine performance and emission by same biofuel. These variations of performance and emission are summarised in Tables 5 and 6.

7. Analysis of engine performance for biofuel

7.1. Brake specific fuel consumption

BSFC refers to consumption of fuel per unit power and in a unit time. Generally using biofuel results in higher BSFC than that of OD fuel [128,129]. As biofuels have higher density and lower calorific value than OD fuel, increase of BSFC is obvious. Injection pressure and atomization rate also have some effects on BSFC. Most of the papers reviewed here reported increase or closely similar BSFC of biofuels compared to OD fuel [59,61,94]. But there were also some exceptions.

Anbumani and Singh [47] found lower BSFC than OD fuel by running the engine with esterified blends of mustard oil. They explained this improvement was due to better combustion of high oxygen containing biodiesel and high cetane number of mustard oil than that of OD fuel. Adding metallic fuel additive also decreases BSFC [130].

7.2. Brake thermal efficiency

As biodiesels have lower calorific value than OD fuel and different biofuels have different calorific values and densities, comparing them in the basis of BSFC could be misleading. For this reason BTE can be considered instead of BSFC. Using biofuels resulted in both increasing and decreasing phenomena regarding BTE [59,131]. However, BTE was improved in cases where crude oils were used without blending and BTE deteriorated for transesterified blends. As crude oil provides higher lubricity, frictional loss is reduced and BTE increased. At partial and no load condition BTE was increased in most of the cases but a slight drop was observed at full load condition. Complete combustion due to high oxygen content and enough time available for combustion are responsible for high BTE than OD fuel at partial and no load condition. But at full load, time taken for complete combustion is decreased, oxygen molecules get small time to change its state to atomic oxygen, hence BTE drops slightly [47,132]. Most reports showed very similar BTE of biodiesels compared to OD fuel. BTE deteriorated in some of the experiments and in such cases, higher viscosity and lower cetane index are responsible for poor thermal performance [90].

7.3. Brake effective power

Most of the research papers reviewed here, reported slight brake power reduction compared to OD fuel, with the increase of biofuel percentage in the blends. Many authors mentioned lower heating values of biofuels and their blends are responsible for this phenomenon. However, other physicochemical properties of biofuel like higher density, viscosity etc. result poor atomization and problems in fuel flow. These are also some justified causes of low power output reported by some researchers. To maintain the same power as obtained by OD fuel BSFC will be higher for the biofuels [49,90].

Some literature reviewed surprisingly found increase in brake power especially in the case of palm biodiesel which may be explained due to higher cetane number and improved combustion. Improved combustion may be resulted due to high oxygen content of biodiesels than OD fuel. Higher flow rate and energy input increases brake power at low speed range [60]. Use of corrosion inhibitors increases brake power effectively [14].

8. Analysis of engine emission for biofuel

8.1. Exhaust gas temperature

Effective use of heat energy contained in the fuel is indicated by EGT. Emission characteristics of biodiesels generally show a wide range of reports regarding EGT [129,131]. Lower value of EGT is an indication of good burning of fuel inside the engine cylinder. As EGT for biofuel remains lower than that of OD fuel, it indicates that the engine is not thermally overloaded though BSFC was higher. Heating value, cetane number, density and kinematic viscosity these four physicochemical properties also have potential impact on EGT. As all discussed biofuels have higher cetane number and lower heating value than OD fuel, ignition delay occurred which results lower EGT [90]. Higher density and kinematic viscosity of biofuel causes poor fuel atomization and leads to EGT reduction.

In most of the reviewed experimental results, EGT increased at full load condition. Causes behind this phenomenon perhaps, high oxygen content and more fuel burning at higher load condition resulted in improved combustion, hence increased EGT. Due to longer physical delay of biofuels some fuel particles do not get enough time to be burnt completely initially after injection and get

burnt at latter part of expansion. As a result, afterburning occurs which leads to high EGT [71].

8.2. Smoke opacity and particulate matter

Soot, heavy hydrocarbons and sulphates these are three main components of PM [69,133]. Typically 40–80% mass of PM is soot. Increasing percentage of water in the biodiesel results incomplete combustion. Incomplete combustion increases organic compounds in the exhaust as a result increases PM emission. On contrary preheated biodiesel ensures better combustion and less PM in the exhaust.

Most of the researchers reported noticeable decrease in smoke opacity and PM emission at high load operation using biofuels [90,134,135]. High load operation results in diffusion combustion which influences the formation of PM. High oxygen content of biofuel aids to overcome this effect by oxidizing most of the soot particles and reducing smoke opacity and PM emission.

Amount of air inside the cylinder, fuel composition and oxygen content are the main factors that influence smoke opacity. Lapuerta et al. [108] explored the effect of alcohol in smoke opacity and found significant difference between the smoke opacity of used cooking oil ethyl and methyl ester.

No clear conclusion can be made about whether smoke opacity and PM emissions depend on the types of biodiesel feedstock or not. WCO and soybean oil were tested on similar engines by Canakci and Gerpen [97] and no significant variation in PM emission observed. Oxygen content is the main factor which effects PM emission and this property remains almost same for all biodiesels.

8.3. Carbon monoxide (CO)

CO is mainly produced due to incomplete combustion of the fuel. Incomplete combustion occurs when flame temperature cools down and progression to CO_2 remains incomplete. When flame front approaches to relatively cool cylinder liner and in crevice volume, combustion process is slowed down and flame front is extinguished. If the air fuel mixture is too rich amount of oxygen becomes insufficient for complete combustion.

Most of the literatures, reviewed in this paper showed a decrease in CO emission while diesel fuel is replaced by different biofuels. However, a few researchers found similar trend and some also reported noticeable increase in CO emission by using biofuel compared to OD fuel. Pure biodiesel produces less CO than the blended one. Emulsified fuel also produces higher CO and amount increases with the increase of water percentage. Addition of water results incomplete combustion hence increases CO [69]. Advancing injection timing also increases CO [136]. Different characteristics of biofuels and load conditions have remarkable impact on CO emission. Increase in saturation level in molecular structure decreases CO emission [137]. CO emission increases with increasing the percentage of acid values in the biofuel. Higher acid value refers to higher hydroperoxide concentration which leads to CHO, HCHO and CO formation [98].

Many results of reviewed article showed less CO emission by using biodiesel than OD fuel which indicates complete combustion of biofuel than OD fuel [48,59,125,134]. Explanation of this finding is additional oxygen content of biodiesel which ensures complete combustion of the fuel. Higher cetane number and lower compressibility of biodiesel compared to diesel fuel reduce the probability of advanced injection and forming fuel rich zone. As a result ignition delay becomes shorter, duration of combustion process increases and combustion gets completed properly, hence reduces CO.

8.4. Hydrocarbon (HC)

Hydrocarbons present in the emission are either partially burned or completely unburned. Generally a sharp decrease in the trend of HC emission is observed while running the engine with biofuel [134,138,139]. However, HC emission is not influenced by types of feedstock which was reported by Canakci and Van Gerpen [97]. They revealed Ethyl ester of crude oil produced less HC than methyl ester which can be explained by lower heat of vaporization of ethyl esters.

Similar to CO emission, HC emission is also resulted from incomplete combustion due to flame quenching at cylinder lining and crevice region. Engines operating conditions, fuel spray formation, fuel properties etc. are some other important HC emission influencing conditions. As the blending percentage, cetane number and oxygen content of the biodiesel increases, hence leads to more complete combustion and combustion efficiency increases. Higher combustion efficiency reduces unburned HC emission. At higher engine speed, as injection pressure is higher and atomization ratio is also increased, HC emission shows similar trend regardless of the fuel type. Enhanced air flow inside engine cylinder at high speed range helps to create more homogeneous mixture and reduces HC emission.

8.5. Nitrogen oxides (NO_x)

The important factors that effect NO_x emission are in cylinder pressure, temperature and oxygen content of the fuel [42,140,141]. A slight increase in NO_x emission was found in most of the literature reviewed [48,59,95]. Some mentioned increase in NO_x emission under certain test and operating conditions. Mustard oil is an exception in this case, as almost all researchers reported NO_x decreasing characteristics of mustard oil at all load and test conditions compared to diesel fuel.

Various reasons are mentioned for the increase of NO_x emission while using biofuels and their blends. Due to their own chemical structures all biofuel contain invariably some level of excessive oxygen compared to OD fuel. In addition to inducted air inside the engine cylinder, oxygenated biofuels add some more oxygen which may influence the formation of NO_x. Higher combustion temperature increases NO_x by stimulating NO_x forming reactions. Improved combustion is resulted due to lower ignition delay and enhanced fuel- air mixing at higher engine speed, which contributes to high in cylinder temperature.

NO_x emission increases with the decrease of mean carbon chain length and increase in unsaturation, hence increase in iodine number. Density, compressibility, cetane number and unsaturation these properties are closely related to iodine value. NO_x emission is directly related to degree of molecular saturation [142,143]. Biofuels having more unsaturated bonds produce more NO_x than saturated biofuels. In fact unsaturated bonds are more reactive and start combustion reactions readily.

Keskin et al. [130] produced metallic fuel additive from the stoichiometric reaction of Resinic acids with NiO and MnO_2. Lower NO_x emissions were obtained by using this additive with biodiesel at all engine speed. Yusaf et al. [60] found NO_x was decreased at low engine speed than OD fuel by using palm biodiesel. At low engine speed due to oxygen deficiency and lower heat release rate, biodiesel produces lower level of NO_x. Adding fuel additives with biofuel, limits the formulation of ions which catalyses the oxidation process. This effect contributes to the lower heat release rate at premixed combustion phase and lowers peak temperature of combustion process, hence reduces NO_x [14]. Low sulphur and aromatics content of biofuels especially mustard oil, may influence low NO_x emission. Fuel spray characteristics like: degree of mixing, size and momentum of fuel droplets, penetration and evaporation

rate etc. effect in the flame region which influences NO_x formation later on. As density and other physicochemical properties of biodiesels are different from general OD fuel, all these may bring about lower NO_x formation than OD fuel.

9. Limitations of biofuel

Massive increase in fuel production from edible feedstock has raised a highly controversial "food vs. fuel" debate which is not new in the international agenda [144]. In present situation more than 95% of biofuel is produced from edible oil source. Rapeseed, palm, sunflower and soybean are the main edible sources of biofuel industry [145]. Use of edible feedstock for producing biofuel puts threat on food security and cultivable land which has been criticized by many environmentalists worldwide. Besides, biofuel feedstock are expensive than diesel fuel. Cost of biofuel feedstock comprises around 70% of the total expenditure involved in the production process. Thus, minimizing the cost of biofuel feedstock has been the main requirement for most biofuel producers around the globe [146]. To ensure food security, one promising option is to establish a multiple non-edible feedstock pattern for biodiesel production. *C. inophyllum*, *Jatropha curcas* and Pongamia pinnata are now being considered as very prospective non-edible feedstock for biodiesel production [147]. Most of them are cultivated in sandy and saline soil, barren land and mountainous area which also put no threat on existing cultivable land. Waste edible oil can also come to aid this situation. All experimental results discussed in the WCO performance and emission section of this paper promote the use of waste portion of edible oil sources. Low quality seed pressed oil can also be used as biofuel feedstock. Use of WCO will not affect the food chain and can reduce the feedstock cost around four times than fresh edible oil feedstock which is represented in Fig. 7. By proper management system, efficient supply chain and promoting non-edible biofuel feedstock can reduce the production cost as well as secure food supply.

10. Conclusion

Biofuel is taking its position every day over OD fuel because of the increasing trend of petroleum price and the environmental advantages. Moreover, industrialization and luxurious lifestyle have increased energy consumption more than ever before, which left no options without depending on renewable alternative fuel sources in near future. Though the use of biofuel is not a new invention but industrial production and establishment of biofuel as a successful alternative to diesel fuel is still a modern, challenging and prospective area for researchers. This paper critically reviews experimental results on fuel properties, performance and emission of four prospective biofuels derived from both edible and non-edible feedstock. However, tremendous demand of edible oil all over the world criticizes edible oils as an ideal feedstock. Thus attention is shifted to non-edible vegetable oils sources like *C. inophyllum*, WCO or inedible low quality MSO.

Following findings are summarized from the review of four specific biofuels:

- High disparity is found in the results of the experiments of different researchers for the same biofuel, specifically regarding BTE and different emission characteristics. Operating conditions, engine selection, different source and qualities of biofuel feedstock, measurement procedures and techniques, measurement device accuracy and precision strongly influence on derived performance and emission. Hence, each research work was specific in nature.
- Palm, WCO and *C. inophyllum* basically contain palmitic, stearic, oleic, linoleic and α-linoleic acid but mustard contains oleic, linoleic, α-linoleic and exceptionally high amount of erucic acid (more than 36%) which reduces its edibility unlike other edible plants of Brassicaceae family.
- Due to lower heating value of biofuels, increasing percentage of biofuel in the blend increases BSFC and decreases brake power.
- Discussed four particular biofuels reduce smoke opacity, HC, PM, CO and CO_2 emissions. All biofuels contain higher amount of oxygen than OD fuel which ensures complete combustion, hence reduce above mentioned pollutants. Amount of oxygen remains almost invariable in all feedstock.
- This opposite trend is to be optimized to get a convenient BSFC while emission pollutants still remain in tolerable level. Hence, further research can be carried out on this trade-off.
- Research works carried out on palm, WCO and *C. inophyllum* biofuels all revealed both NO_x increasing and decreasing characteristics. But all experiments using mustard oil exceptionally showed reduction of NO_x. Using mustard oil reduces NO_x up to 55.55% than that of OD fuel. No clear indication about this special quality of mustard oil was found as a limited research papers are published on this biofuel. Moreover, NO_x emission for biofuels can be reduced by following certain strategies. Retardation of injection timing, improving the cetane number and exhaust gas recirculation are some effective measures can be taken to reduce NO_x.
- As very few published works were found on mustard and *C. inophyllum* oil application as biofuel, quality research can be carried out to bring out them as potential and renewable biofuel feedstock.

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